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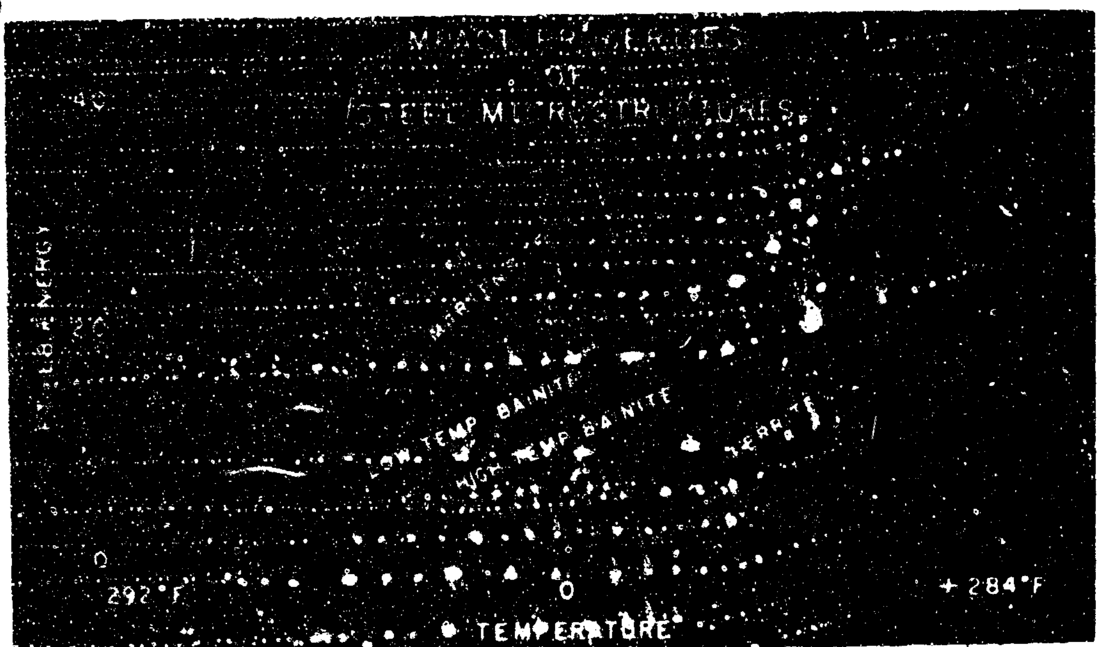
MS-2

Monograph Series

RESEARCH AND DEVELOPMENT OF MATERIALS FOR GUNS AT WATERTOWN ARSENAL LABORATORIES



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at
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RESEARCH AND DEVELOPMENT OF MATERIALS FOR GUNS AT

WATERTOWN ARSENAL LABORATORIES

The Ordnance Corps mission for research and development of ferrous metals has been assigned to the Watertown Arsenal. Implementation of this mission responsibility exists in several areas. Basic research is being conducted on the development of new alloys and on techniques to improve existing alloys. Concurrently, applied research is being conducted on ferrous alloys for particular military applications. Examples of this applied research which have been conducted over a number of years with fruitful results are the armor materials program and the gun materials program. It is the latter of these with which we are concerned today.

Although Watertown Arsenal has been at the forefront of gun materials development for well over 100 years, the period from about 1940 on will be one with which we are concerned. During this period, extensive research has been conducted on the selection of alloys and the processing of these alloys to provide the microstructures and resultant high mechanical properties that modern guns demand. The mechanisms of wear of gun tubes--erosion and progressive stress damage--have been studied extensively and are now quite well understood. Techniques which provide reduced wear and stress damage have been developed to provide gun-barrel materials to withstand some of the conditions imposed by the demand for high-velocity ammunition. Methods of inspecting the materials, and even the finished barrels, by nondestructive techniques have been developed. And last, but far from least, the specification requirements which insure that accepted gun barrels will perform adequately have been developed and incorporated into appropriate procurement specifications. Let us look at some of these factors in more detail.

During World War II some guns were failing in the field in spectacular fashion by what is now termed "brittle failure." Intensive investigations at Watertown Arsenal Laboratories determined that in all these failures toughness was lacking in the barrels. Research in progress on strain rate and notch sensitivity was intensified. It was determined that the effect of increasing the strain rate could be duplicated by reducing the test temperature and that the phenomenon could be observed much more readily in sharply notched specimens. These studies resulted in the development of the V-Notch Charpy impact specimen as a tool which could distinguish the tough from the brittle gun steels.

Concurrently, intensive metallurgical studies concluded that toughness was a function of the microstructure. V-Notch Charpy impact specimens machined from a given steel and broken at temperatures ranging from about +200°F to about -200°F revealed that at some temperature a sharp transition

from tough to brittle behavior existed. One steel sample was divided and each resulting sample heat treated to a constant strength level but with a microstructure different from the others. Curves typical of the resulting impact transition curves are shown in Figure 1. It was determined that the samples having tempered martensitic microstructures provided the lowest transition temperature, or the maximum resistance to brittle failure at low temperature.

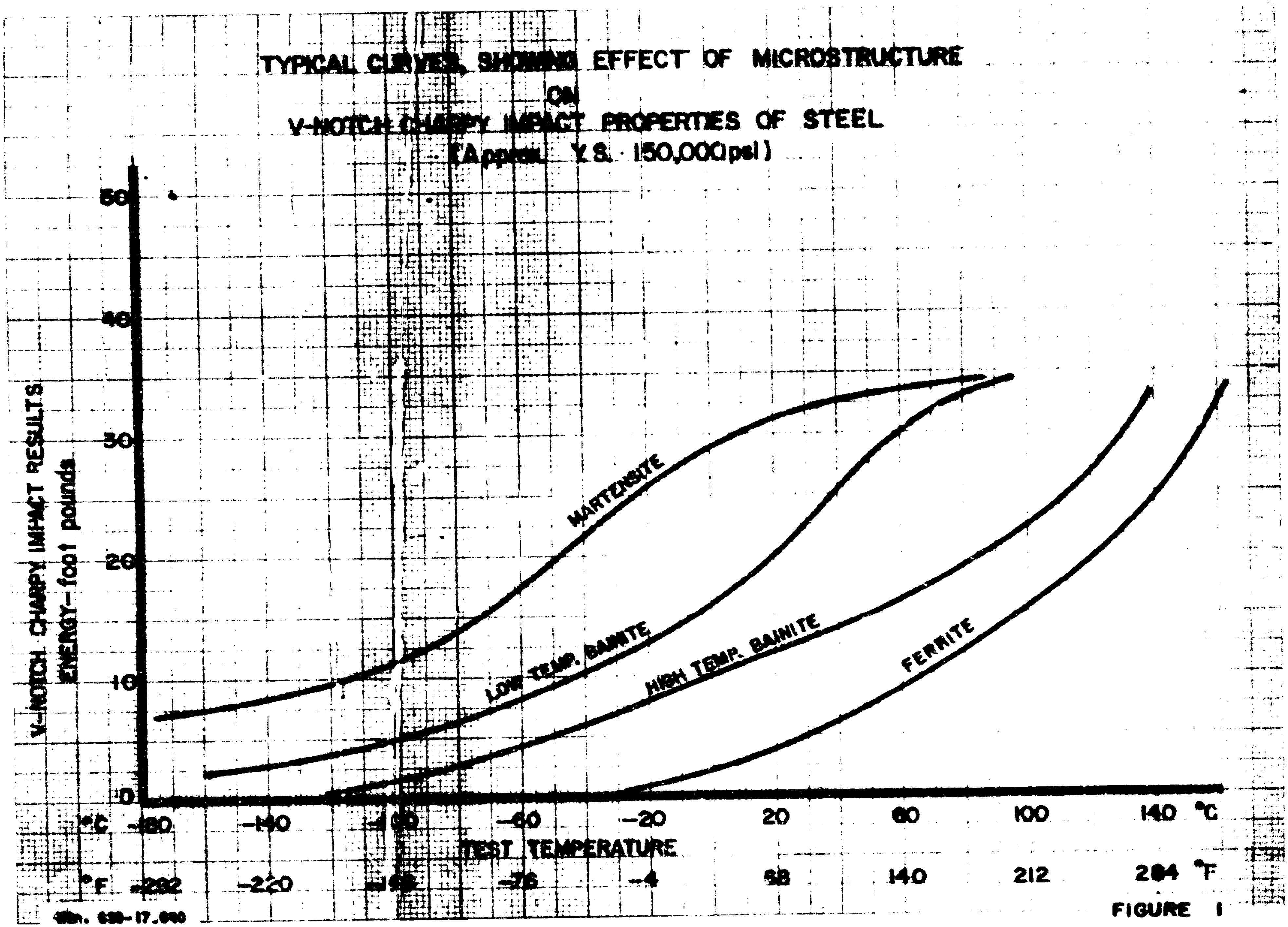
As a result of this research and development activity, the V-Notch Charpy impact test was developed into a specification acceptance test by Watertown Arsenal. For gun steels (or many other alloy steels) the specification of the proper impact requirements at -40°F and a particular strength level will insure that heat treatment has resulted in a tempered martensitic structure. Hence, maximum resistance to brittle fracture has been accomplished. This toughness provision was first incorporated in gun steel specifications in 1946.

More recently, research at Watertown Arsenal has been directed toward the analytic determination of the stress distribution in notched or cracked specimens considering both elastic and plastic deformation. It is hoped that such activity will lead eventually to use of the Charpy impact strength on a quantitative basis for the design of Ordnance components subjected to dynamic loading.

Another prime factor in limiting gun performance is the matter of barrel erosion. Watertown Arsenal has been concerned with bore-protection treatment to minimize erosion and has carried out or supported research and development studies in fields including chromium electroplating, molybdenum vapor deposition, and chromium-base alloys.

Chromium plating, originally adapted by the Navy for protection against corrosion, has proved valuable in improving gun-barrel life in varying degrees. Research supported by Watertown Arsenal has led to the development of chromium-alloy electrodeposits with superior properties to those of conventional chromium plate. An alloy of approximately 90% chromium and 10% iron has been developed which is virtually crack free, can be deposited at rates three to eight times that of regular chromium plate, and shows better retention of hardness than regular plate. The deposit has displayed excellent adhesion and erosion characteristics in recently completed 500-round firing tests in the .60-caliber erosion gauge weapon. Further research on factors affecting control of adhesion are required before scaled-up firing trials can be undertaken on cannon barrels.

Molybdenum is one of the most promising erosion-resistant materials; however, its utilization as a coating is hampered by the lack of a satisfactory commercial method for applying it. As a result of studies sponsored by


TYPICAL CURVES, SHOWING EFFECT OF MICROSTRUCTURE
ON
V-NOTCH CHARPY IMPACT PROPERTIES OF STEEL
(Approx. Y.S. 150,000psi)
V-NOTCH CHARPY IMPACT RESULTS
ENERGY—foot pounds
0
10
20
30
40
50
MARTENSITE
LOW TEMP. BAINITE
HIGH TEMP. BAINITE
FERRITE
°C
-180
-140
-100
-60
-20
20
60
100
140 °C
TEST TEMPERATURE
°F
-292
-220
-148
-76
-4
68
140
212
284 °F
FIGURE 1

Watertown Arsenal at Massachusetts Institute of Technology and National Research Corporation, the formation of vapor deposits of molybdenum by hydrogen reduction of molybdenum pentachloride has reached the development stage. Ability of such coated inserts to withstand the stresses induced by actual firing conditions has been demonstrated.

Watertown Arsenal recognized the value of chromium-base alloys as potential gun-liner materials due to high oxidization resistance, good stress rupture life, and intrinsic erosion resistance, and fostered an extensive alloy-development program which culminated in an industry-wide symposium on ductile chromium in 1955. Research at Watertown Arsenal is currently centered on double-melted 50% chromium binary alloy compositions and is being directed toward fabricating test inserts with controllable mechanical properties. To achieve desired ductility, toughness, and grain size, it appears necessary to utilize combinations of hot and cold mechanical working starting with extruded shapes.

Recent metallurgical studies of materials for guns have been aimed at developing high-strength materials to minimize the weight of artillery weapons. Scientific studies in the field of ultra high-strength materials are being surveyed very closely. Evaluations of many promising, high-strength candidate materials including ultra high-strength steels, titanium alloys, aluminum alloys, and reinforced plastics have been conducted. Internal studies have included high-strength titanium alloys, and at least one alloy (which has been produced in commercial quantities) has been developed having a yield strength of 130,000 psi with satisfactory toughness and ductility.

Since the research and development program on materials for conventional artillery has been quite modest during recent years, emphasis has been placed on increasing the combination of strength and toughness in steel and also conserving strategic alloys. Tough, high-strength steels are required because of increased muzzle velocities and higher internal pressures as well as the desired weight reduction of high-performance weapons for tank and anti-aircraft use. Consequently, metallurgical studies have been guided to work in this area.

A study has been conducted to compare the metallurgical and mechanical properties of steels cold worked to strength with steels heat treated to strength. It has been determined that steels heat treated to relatively low strengths and then cold worked to strength (up to yield-strength levels of 180,000 psi) possess higher impact properties than steels heat treated to high strength. Unfortunately, it has not been possible to obtain quantitative information on the relative service performance of gun tubes in the

two different conditions. Vacuum-melted steels are being considered because of the very high strengths obtainable (more than 200,000 psi yield strength) and the excellent toughness reported at these high strengths. To date, however, no firing tests have been conducted.

Scientific progress in physical metallurgy has been followed quite closely so that new developments can be utilized. In this connection, studies have been conducted to assess the use of rare-earth metals and boron in modified 90MM and 120MM gun steels. Improvements have not been consistent, but the results showed that in several cases rare-earth metals improved impact energy and lowered the transition temperatures in V-Notch Charpy impact tests. The boron, which raises hardenability and thereby permits a reduction in alloy, did not show any consistent improvement in hardenability. The studies have demonstrated the importance of control during processing in order to realize the maximum benefit in hardenability. Therefore, although desirable for reducing the use of strategic alloys, appropriate processing controls (particularly melting and deoxidization practice) must be developed at each production facility before a consistent improvement in hardenability can be obtained.

There is little need to stress the importance of reliable nondestructive testing of gun barrels and components. Because of the possible catastrophic nature of a service failure, it is often necessary to discard barrels before the end of their useful life. Measurements of wear on the bore of a gun barrel can be taken as an indication of the life span; however, no consideration is taken of the serious possibility of failure resulting from the progressive enlargement of small cracks originating in the surface of the bore. It was for this reason that the magnetic recording borescope was developed at Watertown Arsenal. This instrument produces a permanent record on a strip chart of the condition of the bore of the gun barrel. Records of this type taken at intervals through the service life of the gun will provide an accurate and reliable indication of the rate of progression of damage in highly stressed areas. Thus, the life of the gun is realistically determined by the direct measurement of the actual factor contributing to the failure of the barrel.

A recent innovation for the nondestructive inspection of new machine gun barrels to assess the adequacy of heat treatment during manufacture has been developed at Watertown Arsenal. Essentially, it is based upon two different methods of examining microstructure nondestructively and depends for its operation upon the fact that different microstructures exhibit both different magnetic behavior and the high-frequency sound transmission characteristics.

In the magnetic test the barrel to be inspected is compared by means of a very sensitively balanced magnetic bridge-type of circuit with one

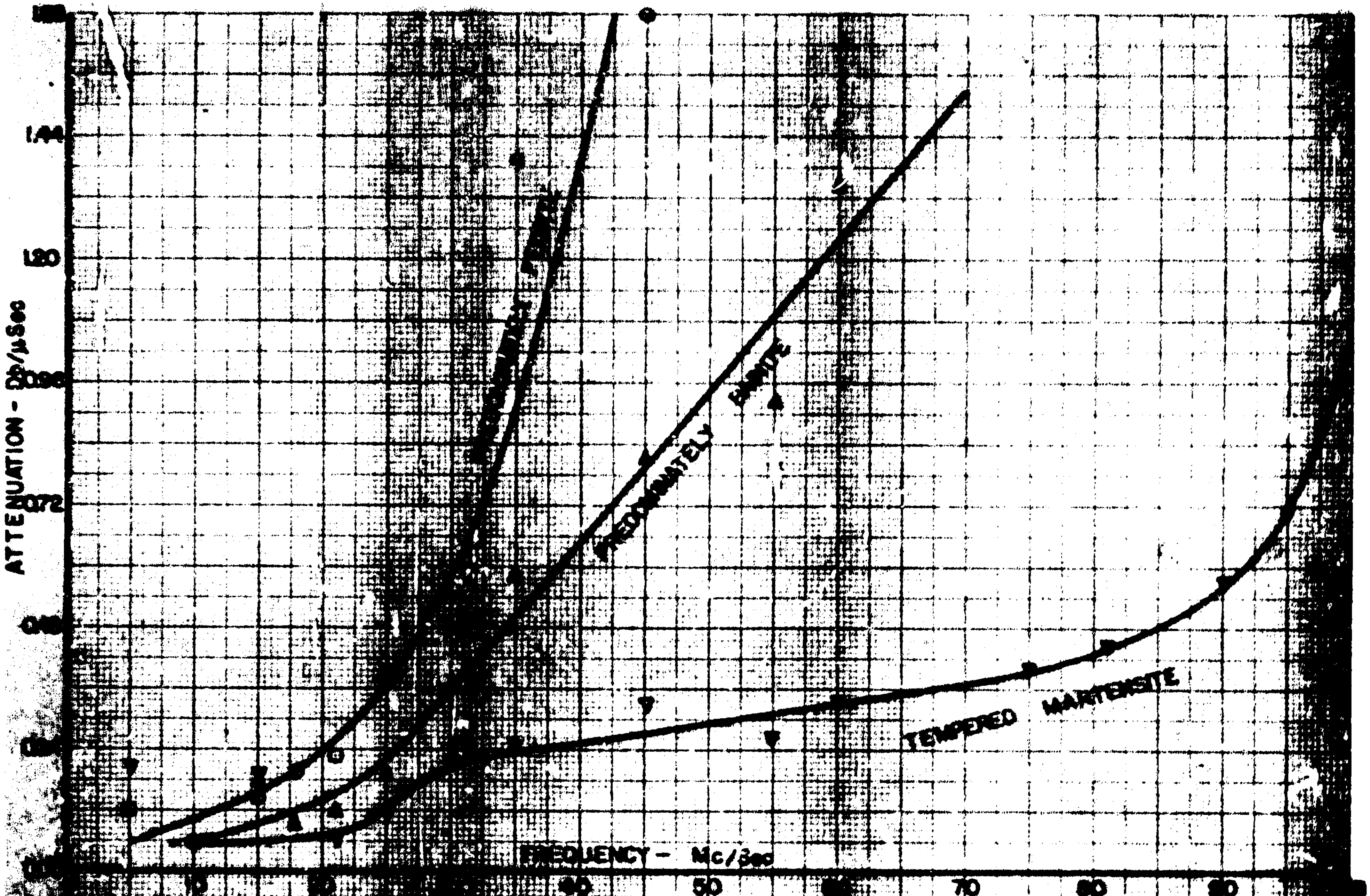
that is known to have been correctly heat treated. When performed under carefully controlled conditions any resulting unbalance can only be due to such factors as surface imperfections or a nonmartensitic microstructure resulting from inadequate heat treatment. Both are rejectable conditions. The degree of unbalance which can be tolerated for a particular barrel design can only be fixed after exhaustive tests and correlation work.

The test based upon the high-frequency sound transmission characteristics consists of measurement of the ultrasonic attenuation at a frequency of 50 megacycles per second. Ultrasonic attenuation in a solid is a rather involved function of many variables but becomes more and more dependent upon "scattering" as the frequency rises to the high megacycle range as shown in Figure 2. In the range between about 35 to 90 megacycles, the fine homogeneous microstructure of tempered martensite exhibits very little scattering effect; while the coarser and less homogeneous bainitic and ferritic microstructures are responsible for a considerable amount of attenuation due to scattering. In the figure, the curve on the right represents a martensitic gun barrel. Thus, ultrasonic attenuation measurements carried out within this range of frequencies, and under carefully controlled conditions, provide a powerful tool for the nondestructive determination of microstructure.

The magnetic test which thoroughly checks the barrel outer surface layer and the ultrasonic attenuation test which checks the average microstructure existing in the barrel cross section are used as a double test for the adequacy of heat treatment. That these tests are very successful can best be demonstrated as follows: Watertown Arsenal recently inspected well over 100,000 20MM machine gun barrels with these nondestructive tests to separate barrels most susceptible to brittle fracture--that is, containing nonmartensitic constituents in the microstructure. A portion of the test setup is shown in Figure 3.

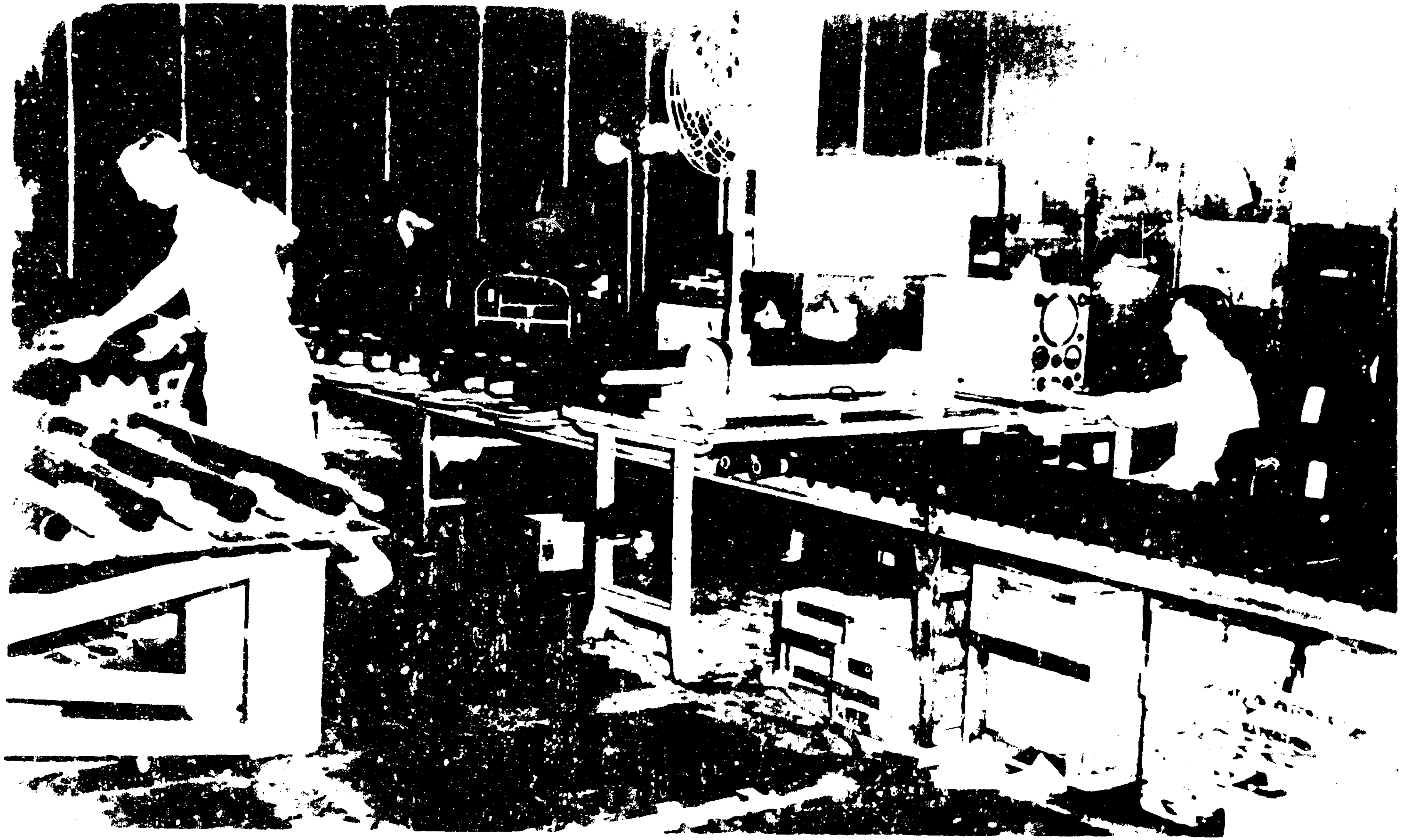
Watertown Arsenal is also involved in the Vigilante system to determine the effect of vibrations induced by the high rate of fire on the aiming accuracy. A 1/4 scale model was constructed and is shown under static test in Figure 4. The static tests are essential to measure deflections which will be used for the vibration analysis. The vibration analysis will be conducted with the aid of the analog computer which is shown in Figure 5. The analysis involving many degrees of freedom and several nonlinear parameters will assess the effect of the various parameters on the aiming accuracy.

The most rec[illegible] activity at Watertown Arsenal has been concerned with the development and processing of high-strength titanium alloys for use in



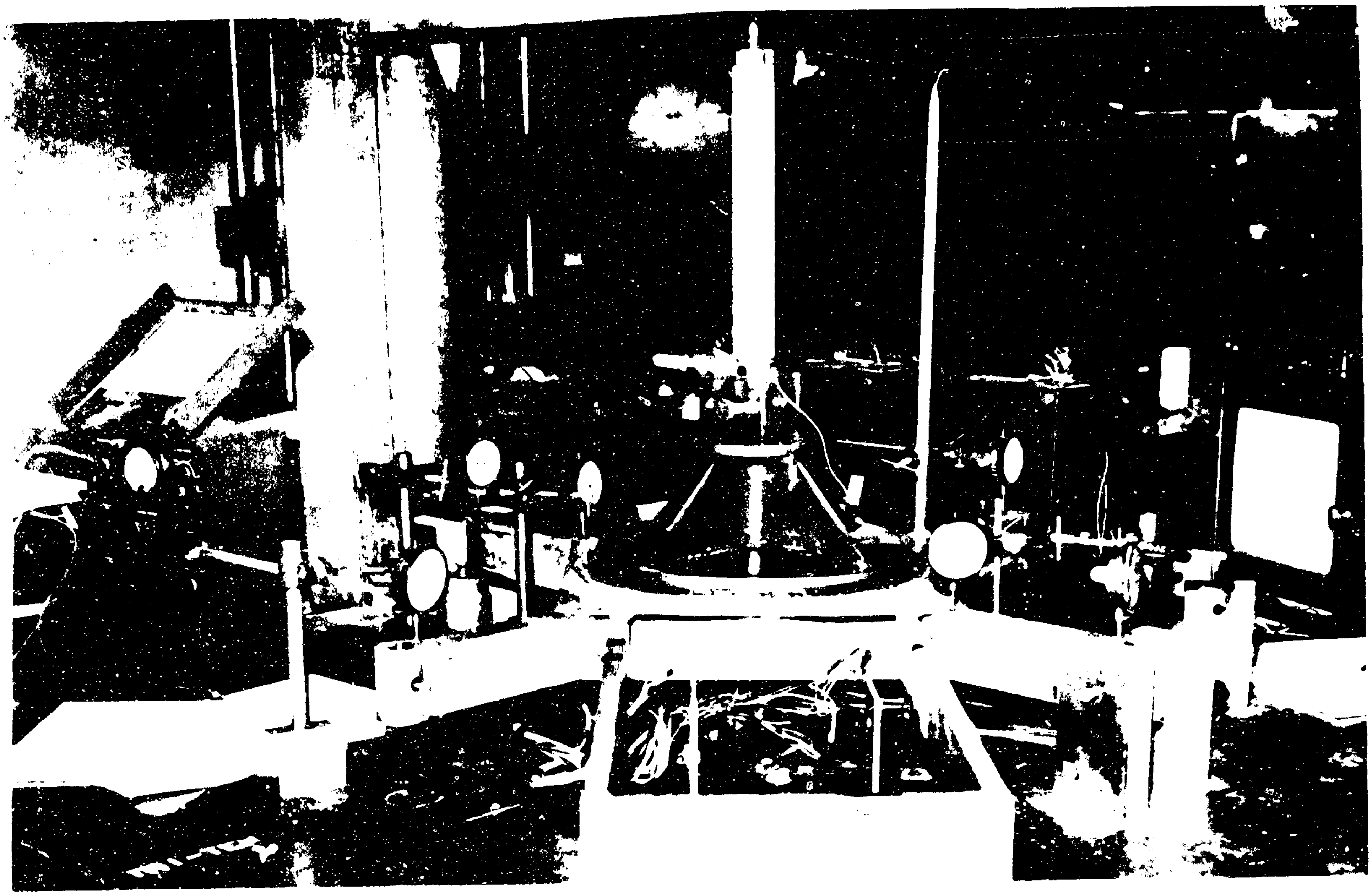
ATTENUATION ... FREQUENCY CURVES

THE MAN ON THE LEFT IS PLACING CONTAINER ON THE LINE LEADING TO ULTRASONIC TESTING DEVICE. ACTUALLY TWO LINES LEAD TO THE TWO ULTRASONIC TESTERS.



Wtn. 639-16,798

FIGURE 3

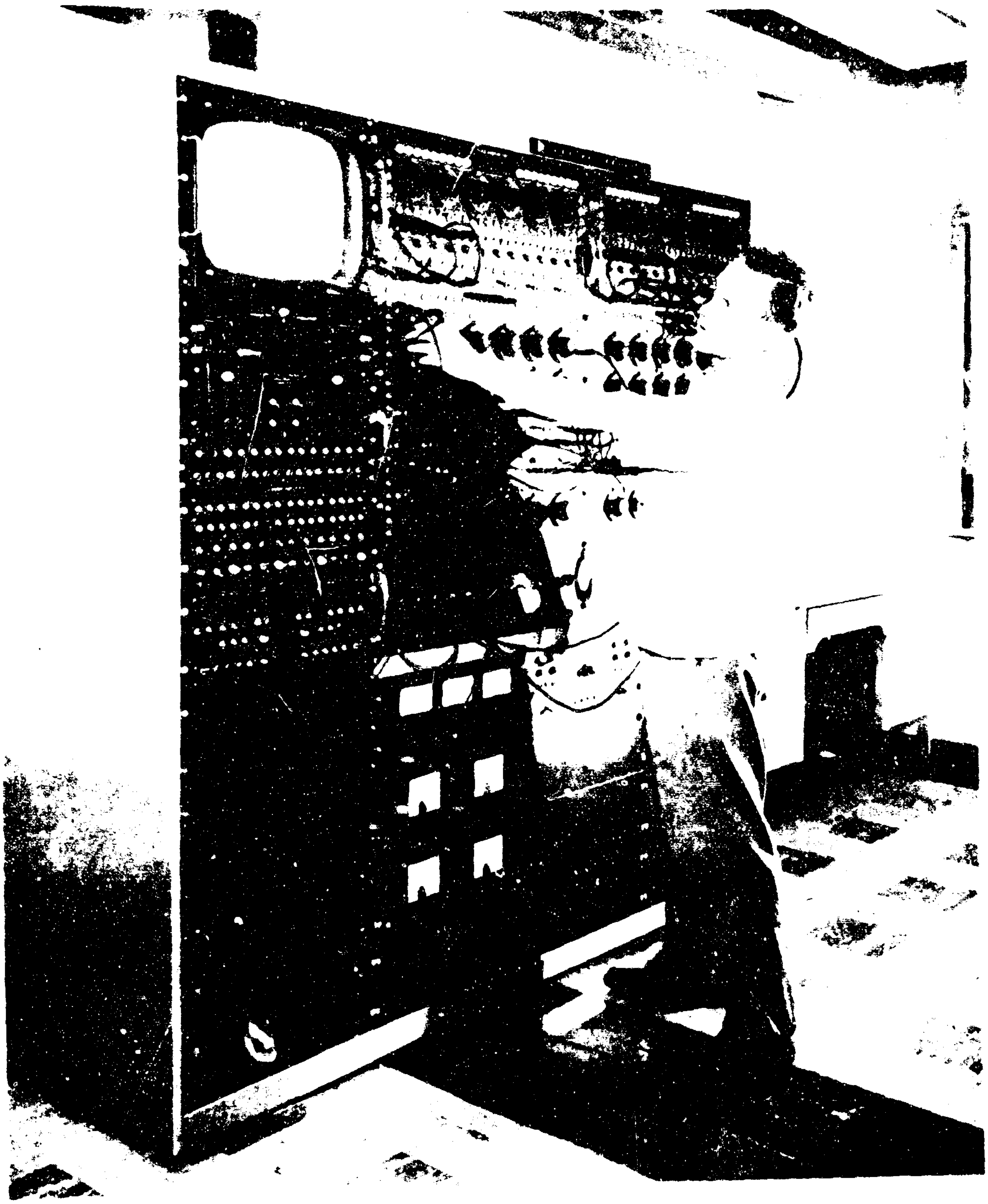


$\frac{1}{4}$ SCALE MODEL, TEST DESIGN OF VIGILANTE BOTTOM CARRIAGE UNDER STATIC DEFLECTION TEST

WTN 932 - 68

FIGURE 4

THE MAN ON THE LEFT IS PLACING CONTAINER ON THE LINE LEADING TO ONE ULTRASONIC TESTING DEVICE. ACTUALLY TWO LINES LEAD TO THE TWO ULTRASONIC



WATERTOWN ARSENAL ANALOG COMPUTOR

FIGURE 5

WTN 681-1249

advanced weapons systems. Typical of the properties obtained in these aluminum-vanadium and aluminum-vanadium-tin titanium alloys by suitable heat treatment are those contained in Figure 6. Notice that in all cases, the tensile and yield strengths have been increased without sacrifice of tensile ductility of V-Notch Charpy impact strength. Notice too, that the highest yield strength listed is 182,000 psi which is equivalent to 310,000 psi in steel on a strength-weight ratio basis. It is also of interest to note that these alloys are all being produced commercially by more than one producer.

There is a marked difference between titanium and steel in that grain refinement in steel can be accomplished subsequent to hot working by suitable heat treatment, whereas in titanium, grain refinement can only be obtained by hot working requiring close temperature-cycle control. Figure 7 shows the tremendous difference in grain size when specimens are heated to temperatures just below the beta transus in one case, and just above the beta transus in the other. For hot working of titanium alloys, then, the position of the beta transus is of critical importance. The situation is further complicated by the rather pronounced effect of alloying elements on the position of the beta transus as shown in Figure 8. The alpha forming elements are shown on the left and the beta stabilizers are shown on the right. From these figures it is obvious that the alloy composition must be known quite accurately before hot working can be specified.

Use of these alloys in Ordnance special weapons items required the development of processing techniques to form them into usable shapes at minimum cost. While these techniques were being developed, tubular parts were machined from billets by trepanning as shown in Figure 9. The fact that this was the first successful trepanning accomplished on titanium alloys was an accomplishment coincidental to the over-all program. Nevertheless, trepanning provided a means for fabricating the parts required initially, and the trepanned core was available for research and development work to further improve the alloy properties.

Various forging and extrusion techniques were developed which permitted fabrication of critical parts for ammunition components. Successful firing tests of these items proved that titanium alloys are now engineering alloys worthy of consideration for Ordnance use where impact loading is involved and particularly where minimization of weight is important. Modification of these processing techniques were developed for fabrication of components for various high-strength, lightweight artillery and automotive systems. Examples of experimental forged titanium tank-track components are shown in Figure 10.

In one of the research and development recoilless rifle developments a three-piece construction was used. This construction is an expedient since each component can be fabricated to the high strength required with

4. OBSERVE MICROSTRUCTURE (SEE PHOTOMICROGRAPHS ...

FIGURE 7

Wtn. 630-16,693

TYPICAL ENGINEERING PROPERTIES OF TITANIUM ALLOYS

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ALLOY-TYPE	Y.S.(.1%) MINIMUM REQUIREMENT (P.S.I. X 1000)	Y. S. (.1%) (P.S.I. X 1000)	T. S. (P.S.I. X 1000)	ELON. (%)	R. A. (%)	V-NOTCH CHARPY IMPACT (FT-LBS)(-40°F)
6AL – 4V	130	135	155	13	38	12 – 16
6AL – 4V 7AL – 4V	140	145–155	160–170	10 – 12	20 – 30	9 – 12
7AL – 4V	150	152	160	12	28	9 – 12
Ti – 155A 5.5AL-5.5V-2SN	170	171	185	12	33	10
5.5AL-5.5V-2SN	185	182	192	13	42	10

NOTE: ALL PROPERTIES ABOVE WERE EVALUATED FROM TRANSVERSE SPECIMENS HEAT TREATED IN A MINIMUM OF 1" SECTION SIZE.

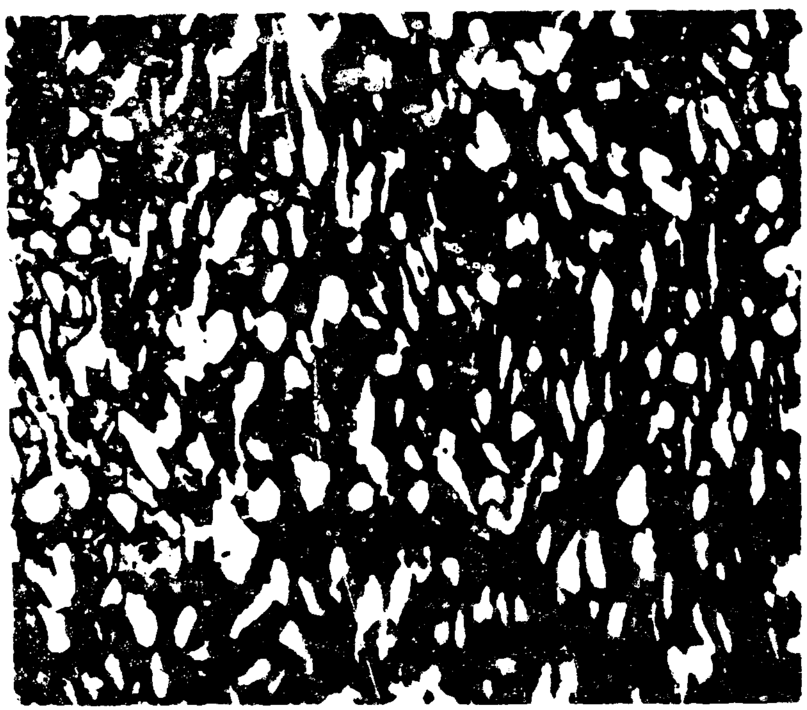
Wtn. 630-16,736

FIGURE 6

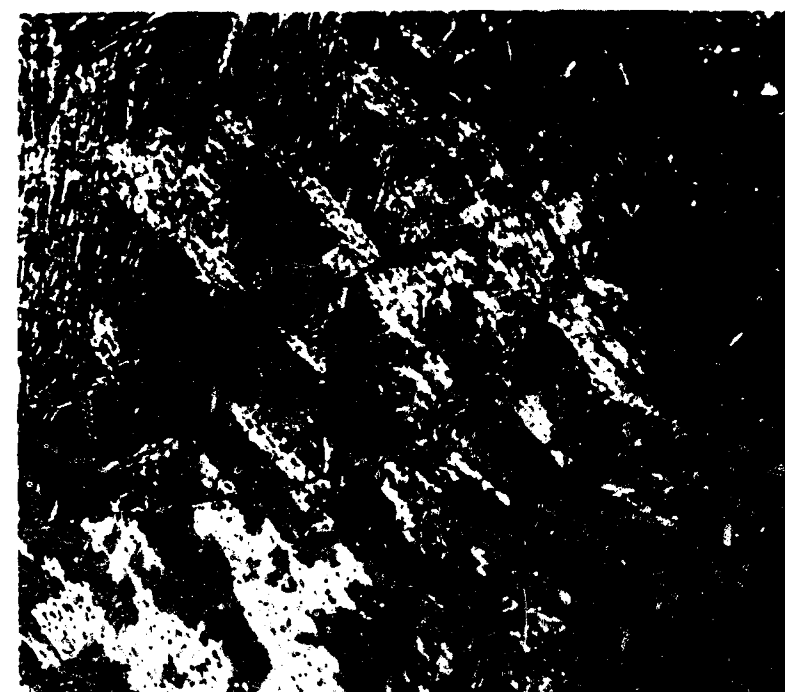
TITANIUM

BETA TRANSUS DETERMINATIONS — METALLOGRAPHIC EVALUATION

WATERTOWN ARSENAL LABORATORIES



BELOW β TRANSUS TEMP.



ABOVE β TRANSUS TEMP.

DETERMINATION PROCEDURE:

1. HEAT $\frac{1}{2}$ INCH TITANIUM TEST CUBE TO 2000°F IN EVACUATED QUARTZ TUBE.
2. FURNACE COOL TUBE CONTAINING SPECIMENS.
3. REMOVE SPECIMENS AND RE-HEAT IN AIR TO SELECTED TEMPERATURES ±75°F OF CALCULATED BETA TRANSUS TEMPERATURES AND FOLLOW BY WATER QUENCH.
4. OBSERVE MICROSTRUCTURE (SEE PHOTOMICROGRAPHS ABOVE).

FIGURE 7

"BETA TRANSUS DETERMINATIONS"

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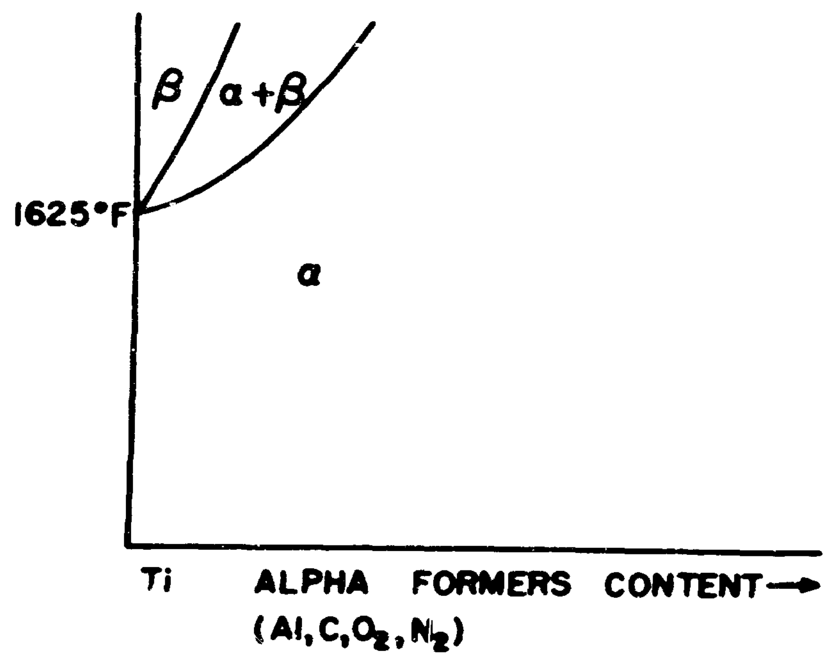
EFFECT OF ELEMENTS ON BETA TRANSUS (BASED ON BINARY TITANIUM SYSTEMS)

(BASE TEMPERATURE = 1625°F

ELEMENT	% RANGE	EFFECT	CUMULATIVE EFFECT	
Al	0-2%	+26°/1%	2%	+ 52°
Al	2-7%	+41°/1%	7%	+257°
Al	7-11%	+28°/1%	11%	+369°
Al	11-20%	+18°/1%		
C	0-0.16%	+5°/.01%		
N_2	0-0.5%	+10°/.01%		
O_2	0-1%	+3.5/.01%		

ELEMENT	% RANGE	EFFECT	CUMULATIVE EFFECT	
H_2	0-0.5%	-1°/.001%		
Fe	0-15%	-3°/0.1%		
Cb	0.10%	-15°/1%		
Cr	0.7%	-25°/1%	7%	-196°
Cr	7-15%	-22°/1%		
Mn	0-20%	-29°/1%		
Mo	0-5%	-10°/1%		
Mo	5-30%	-18°/1%		
V	0-10%	-25°/1%	10%	-250°
V	10-18%	-18°/1%		
Zr	0-10%	-5°/1%		
Cu	0-7%	-22°/1%		



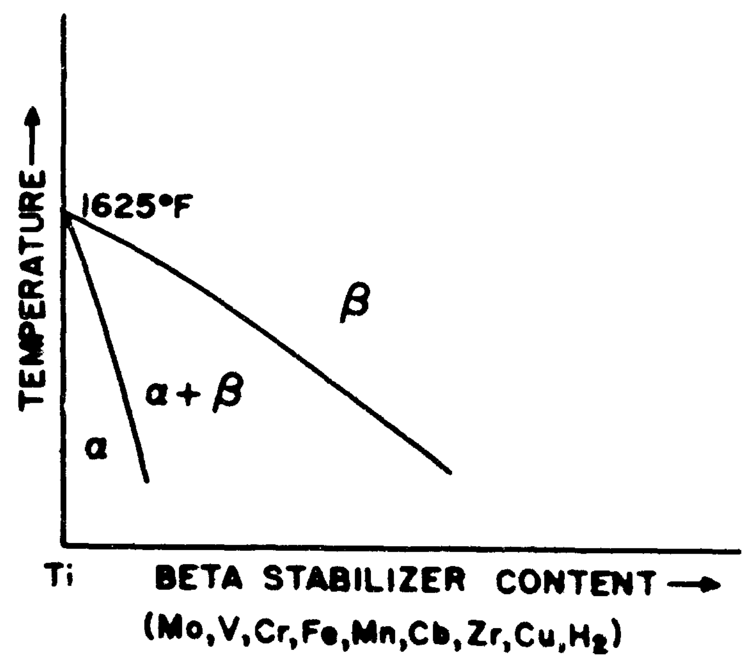


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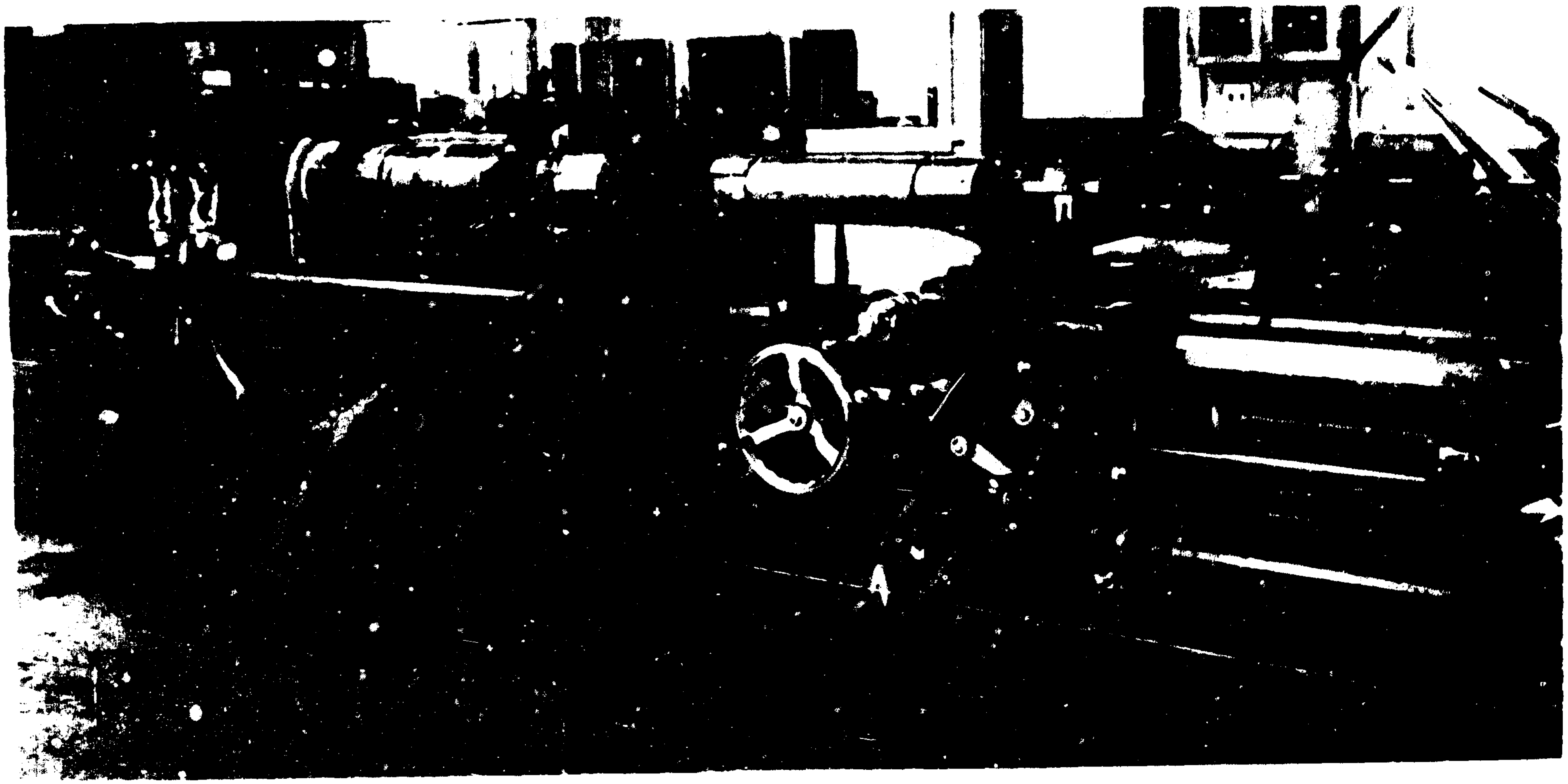
FIGURE 8



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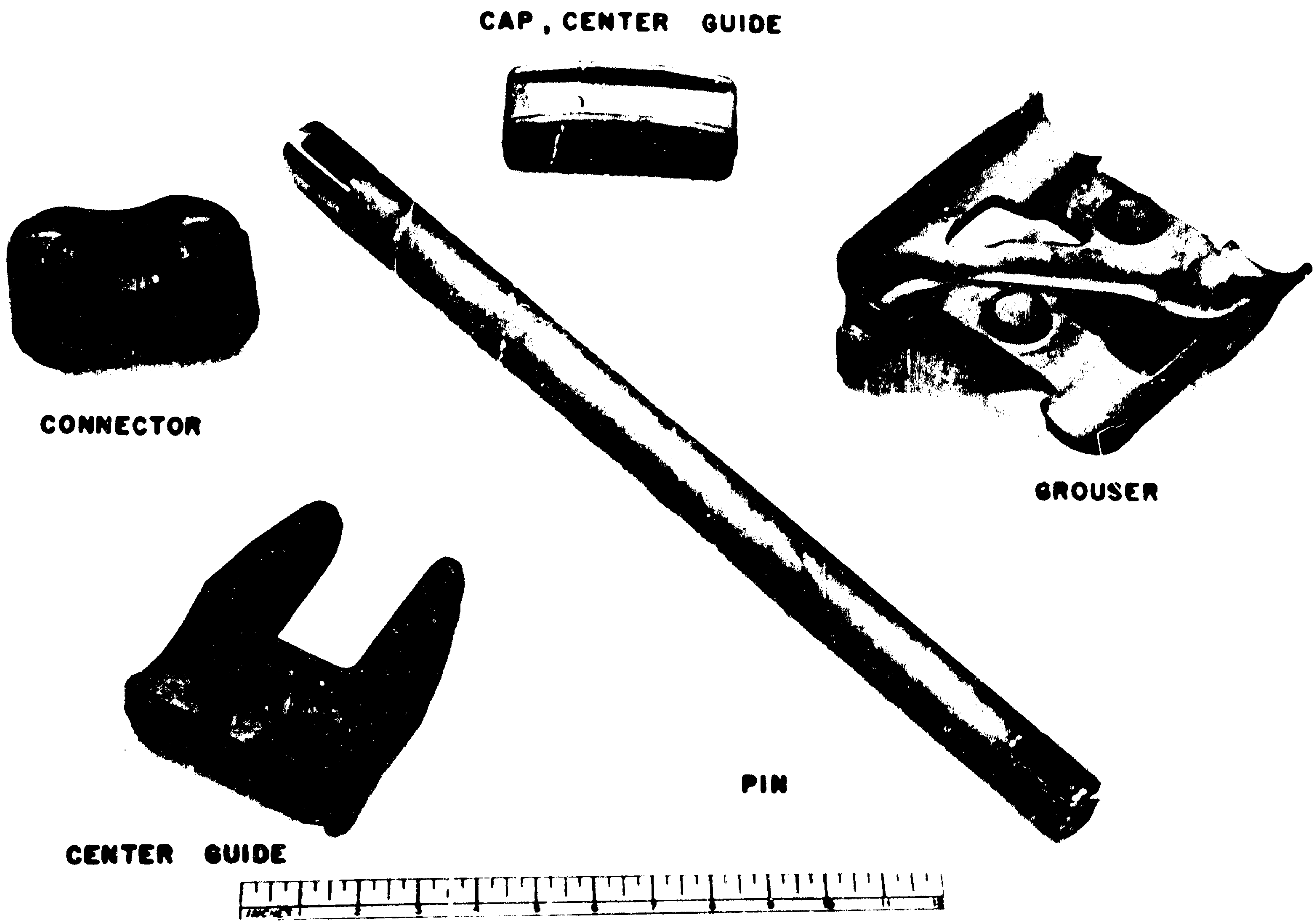
SET-UP FOR TREPANNING OF TITANIUM ALLOY

FIGURE 9



FORGED TITANIUM TANK TRACK COMPONENTS

FIGURE 10

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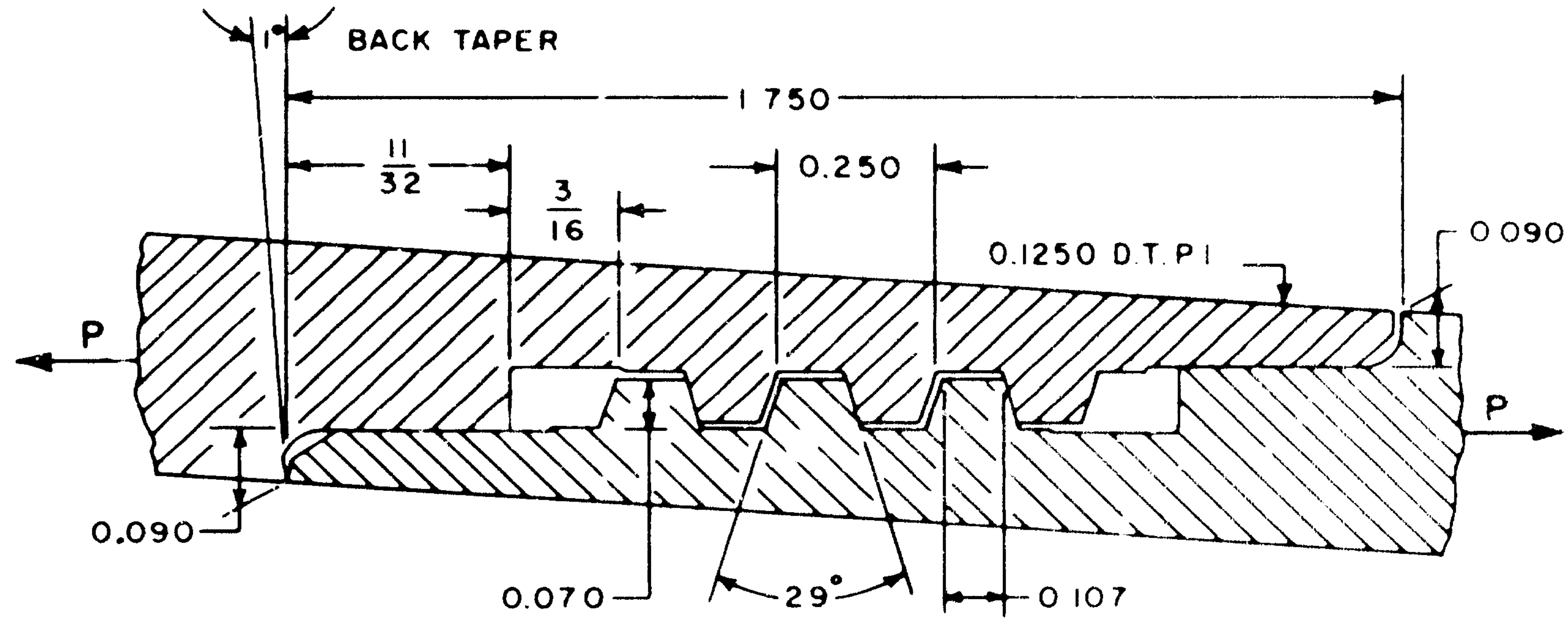
W.T.N. 661-1216

guaranteed results, whereas fabrication of a monobloc gun would require development of suitable fabrication processes. The three components are connected with threaded joints as shown in Figure 11. A special reduced height thread was designed to minimize weight; gas sealing was accomplished with a copper gasket; and an epoxy resin was used to semi-permanently lock the sections together. As shown in Figure 12, these joints were devised from stress-analysis calculations. The adequacy of the joint was proven in firing tests.

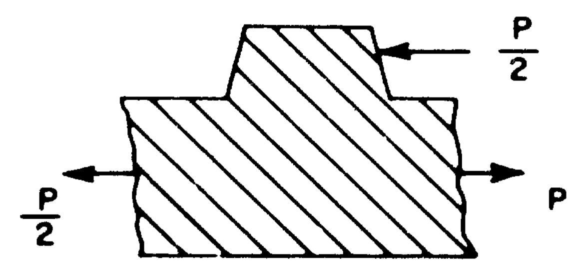
The importance of the use of high-strength titanium alloys in the recoilless rifles cannot be over-emphasized. Weight savings of 40% were realized by meeting the same mechanical-property requirements which were specified for alloy steel. The experimental recoilless gun made from steel weighs about 75 pounds and is not considered manportable, while the experimental gun made of titanium alloys weighs only 43 pounds and is manportable. Although the materials cost ratio per pound of steel to titanium alloy is about 10 to 1, the over-all cost of the item made of titanium is approximately 150% of the cost of the item made of steel. In addition, the water-quenched aluminum-vanadium-tin titanium alloy exhibits excellent high-temperature properties. The yield strength at a temperature of 900°F is 100,000 psi.

As a result of the success of this titanium alloy in recoilless rifles, modified compositions of other titanium alloys are being investigated. Preliminary results indicate that yield strengths of over 200,000 psi can be obtained with adequate toughness and ductility. This success indicates that yield strengths exceeding 200,000 psi will become a reality in the very near future. When such strengths are obtained, titanium alloys will achieve new prominence in weaponry because they will possess far higher strength-weight ratios than any other engineering material.

FIGURE 12



TYPICAL CROSS SECTION SHOWING MODIFIED ACME THREAD
AND APPLIED LOADS



LOAD DISTRIBUTION
ON THREADS

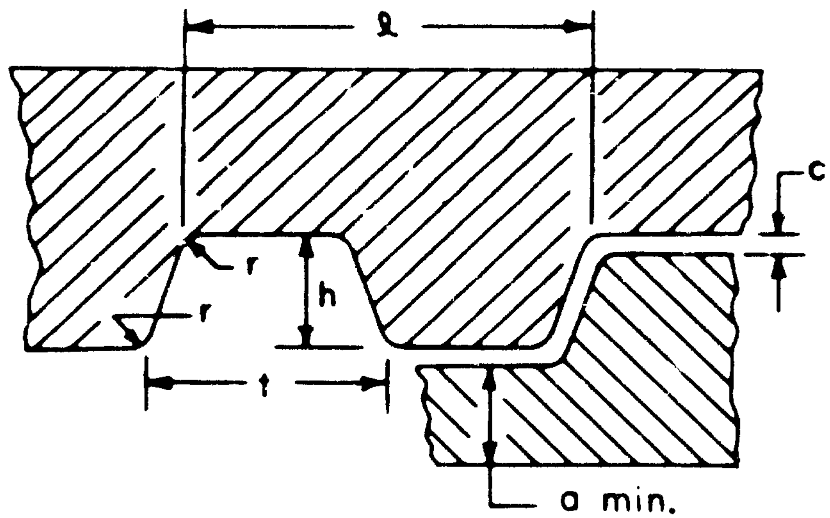
FOR THE CASE OF PULL – PULL LOADING (AS INDICATEC ABOVE) WITH MORE THAN TWO FULL THREADS ENGAGED AND THE NUT & BOLT OF EQUAL STIFFNESS, THIS DISTRIBUTION MAY BE SHOWN TO BE CONSERVATIVE BY USE OF AN ELECTRICAL ANALOGUE (SEE W.A.L. REPORT 893/166*)

* J. I. BLUHM AND J. H FLANAGAN
"A PROCEDURE FOR THE ELASTIC STRESS ANALYSIS OF THREADED CONNECTIONS, INCLUDING THE USE OF AN ELECTRICAL ANALOGUE."

EXPERIMENTAL RECOILLESS RIFLE TUBE THREADED CONNECTION

Wtn. 630-16,736

FIGURE 11



$\ell = 0.250''$
$h = 0.070''$
$r = 0.016''$
$c = 0.005''$
$t = 0.143''$
a min. $= 0.153''$
P = THE TOTAL AXIAL LOAD = 8520 lb/in

SHEAR STRESS $\tau = \frac{P}{\ell} = 34{,}000$ P.S.I.

TENSILE FILLET STRESS $\sigma_t = \frac{3}{2}\, k_t^{*}\, \frac{P(h+c)}{t^2} = 130{,}000$ P.S.I.

BEARING STRESS $\sigma_b = \frac{1}{2}\, \frac{P}{h-2r-c} = 130{,}000$ P.S.I.

NET SECTION STRESS $\sigma_n = k_t^{**}\, \frac{P}{a \text{ min.}} = 125{,}000$ P.S.I.

$k_t^{*} = 2.8$ ("UNIV. ILLINOIS EXP. STA. BULL. 335 (1942)" BY T.J. DOLAN & E.L. BROGHAMER)

$k_t^{**} = 2.1$ ("STRESS CONCENTRATION DESIGN FACTORS" BY K.E. PETERSON, FIGURE 57)

STRESS ANALYSIS OF THE EXPERIMENTAL RECOILLESS RIFLE
TUBE THREADED CONNECTION

Wtn. 639-16,721

FIGURE 12